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Hydrothermal exploration of mid-ocean ridges: Where might the largest sulfide deposits be forming?

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ABSTRACT

Here, we review the relationship between the distribution of modern-day seafloor hydrothermal activity along the global mid-ocean ridge crest and the nature of the mineral deposits being formed at those sites. Since the first discovery of seafloor venting, a sustained body of exploration has now prospected for one form of hydrothermal activity in particular – high temperature "black smoker" venting – along >30% of the global mid-ocean ridge crest. While that still leaves most of that ~60,000 km continuous network to be explored, some important trends have already emerged. First, it is now known that submarine venting can occur along all mid-ocean ridges, regardless of spreading rate, and in all ocean basins. Further, to a first approximation, the abundance of currently active venting, as deduced from water column plume signals, can be scaled linearly with seafloor spreading rate (a simple proxy for magmatic heat-flux). What can also be recognized, however, is that there is an "excess" of high temperature venting along slow and ultra-slow spreading ridges when compared to what was originally predicted from seafloor spreading/magmatic heat-budget models. An examination of hydrothermal systems tracked to source on the slow spreading Mid-Atlantic Ridge reveals that no more than half of the sites responsible for the "black smoker" plume signals observed in the overlying water column are associated with magmatic systems comparable to those known from fast-spreading ridges. The other half of all currently known active high-temperature submarine systems on the Mid-Atlantic Ridge are hosted under tectonic control. These systems appear both to be longer-lived than, and to give rise to much larger sulfide deposits than, their magmatic counterparts — presumably as a result of sustained fluid flow. A majority of these tectonic-hosted systems also involve water–rock interaction with ultramafic sources. Importantly, from a mineral resource perspective, this subset of tectonic-hosted vent-sites also represents the only actively-forming seafloor massive sulfide deposits on mid-ocean ridges that exhibit high concentrations of Cu and Au in their surface samples (>10 wt.% average Cu content and >3 ppm average Au). Along ultraslow-spreading ridges, first detailed examinations of hydrothermally active sites suggest that sulfide deposit formation at those sites may depart even further from the spreading-rate model than slow-spreading ridges do. Hydrothermal plume distributions along ultraslow ridges follow the same (~50:50) distribution of "black smoker" plume signals between magmatic and tectonic settings as the slow spreading MAR. However, the first three "black smoker" sites tracked to source on any ultra-slow ridges have all revealed high temperature vent-sites that host large polymetallic sulfide deposits in both magmatic as well as tectonic settings. Further, deposits in both types of setting have now been revealed to exhibit moderate to high concentrations of Cu and Au, respectively. An important implication is that ultra-slow ridges may represent the strongest mineral resource potential for the global ridge crest, despite being host to the lowest magmatic heat budget.

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1. Introduction

Nearly 40 years after the first discovery of seafloor hydrothermal venting and associated massive sulfide deposits at mid-ocean ridges (Corliss et al., 1979; Francheteau et al., 1979; Spiess et al., 1980), high temperature "black smoker" hydrothermal systems are now known to occur in all ocean basins and along mid-ocean ridges of all spreading rates (German and Seyfried, 2014). Close to 300 high-temperature "black smoker" hydrothermal fields are already known along the ~60,000 km of the global Mid-Ocean Ridge (MOR) system of which 113 have been visually confirmed and a further 159 have been inferred from systematic water column plume surveys (Beaulieu et al., 2013). Statistical interrogation of the global InterRidge vents data-base allows us to predict that a further ~800 MOR vent-sites remain to be discovered, predominantly along slow-spreading ridges (defined as <55 mm/yr full spreading rate; Beaulieu et al., 2015).

Our current state of knowledge (Fig. 1) has been attained through a concerted effort to explore systematically along the global ridge crest, first to understand what geological processes might control the global distribution of such high-temperature venting (e.g. Baker et al., 1996; German et al., 1996) and later augmented with further questions concerning what controls the biogeography of endemic vent fauna (e.g. Van Dover et al., 2002; German et al., 2011). As a result, approximately decadal reviews of the current state of the art, as embedded in the global InterRidge vents database, have allowed us to progress from knowledge of vent-distributions along less than 10% of the global system to more than 30% of the ~60,000 km mid-ocean ridge crest having been surveyed (Baker et al., 1995; Baker and German, 2004; Beaulieu et al., 2015).

An important consideration concerning how our understanding of the global distribution of ridge-crest venting has progressed over the past 3 decades is that we have explored, primarily, for one specific form of hydrothermal activity — the high temperature fluid flow that is emitted from "black smoker" vents and results in characteristic particle-laden plumes that can be detected readily from water column surveys using CTD-rosette systems or, increasingly, using purposefully designed MAPR instruments that have revolutionized the international community's ability to explore for hydrothermal activity in parallel with co-registered petrologic and geophysical investigations (Baker et al., 2004). In this paper we combine insights obtained from two sources: (a) our progressively expanding understanding of hydrothermal vent distributions as determined from hydrothermal plume surveys and (b) direct field observations of active high-temperature hydrothermal fields that have been tracked to source beneath such plumes, along slow- and ultraslow-spreading ridges.

An important goal, in conducting this review, has been to investigate as to what extent future predictions could be made, from hydrothermal plume studies alone, about the nature of any underlying vent-sources and, specifically, about the size and characteristics of the seafloor massive sulfide deposits that they might form. Recognizing that styles of hydrothermal venting exhibit increasing geologic diversity (including the sizes of seafloor massive sulfide deposits) at decreasing spreading rate (e.g. Fouquet et al., 2010; German and Seyfried, 2014) we use the relatively well-studied slow-spreading central Mid-Atlantic Ridge (8°S–45°N) as a test case for these studies. A key motivation is to be able to predict what might await discovery based on hydrothermal plume investigations elsewhere along slow and ultra-slow spreading ridges. Each of these classes of spreading rate represent ~25% of the cumulative length of the global Mid-Ocean Ridge system and it is along these slow- or ultra-slow spreading ridges, recent studies have predicted, that the majority of both seafloor massive sulfide deposits and active hydrothermal fields remain to be discovered (Hannington et al., 2011; Beaulieu et al., 2015).

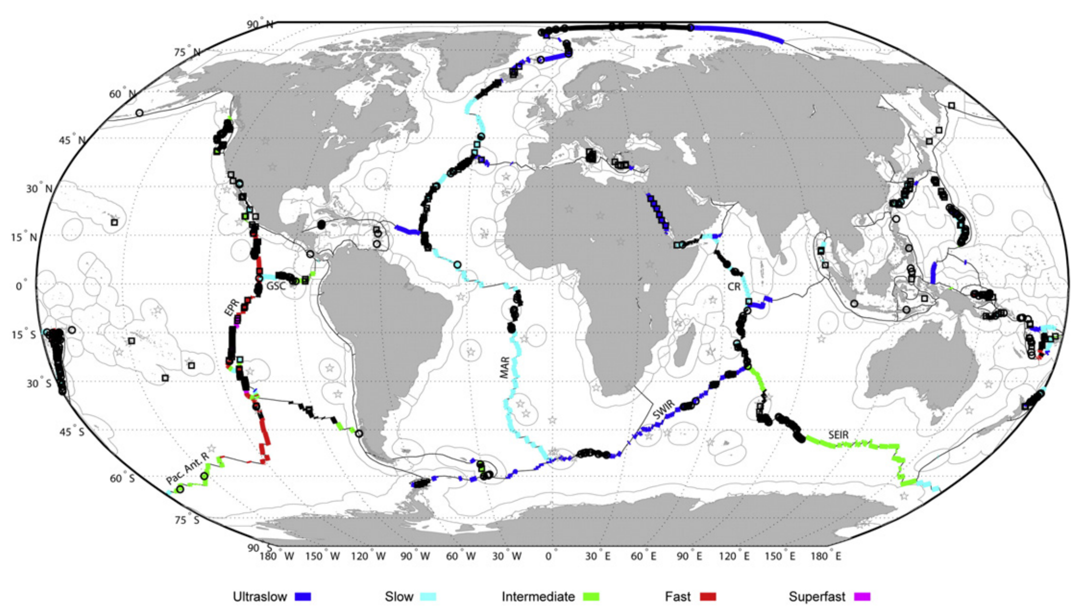

Fig. 1. Distribution of confirmed and inferred active submarine hydrothermal fields, worldwide, along the global mid-ocean ridge system. Ridge segments that have not yet been surveyed for hydrothermal activity are color-coded according to five spreading-rate categories: ultraslow (0–20 mm/yr full spreading rate); slow (20–55 mm/yr); intermediate (55–80 mm/yr); fast (80–140 mm/yr) and superfast (>140 mm/yr). The focus of this review falls primarily upon high-temperature "black smoker" venting along the slow and ultra-slow ridges that constitute ~50% of the cumulative length of the 60,000 km global mid-ocean ridge axis, including a continuous sequence from the Gakkel Ridge in the Arctic, via the Mid-Atlantic Ridge and SW Indian Ridge to the Rodriguez Triple Junction, Central Indian Ocean. Figure reproduced, with permission, from Beaulieu et al. (2015).